TITLE: **Enhanced Practical Photosynthetic CO_2 Mitigation**

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ABSTRACT

Biological carbon control, or photosynthesis, offers many advantages. Biomass developed from photosynthesis has numerous beneficial uses, including a potentially renewable source of hydrogen. It also offers potentially very low operating costs. The work presented here, partially funded by the Department of Energy under grants DE-FG2699-FT40592 and DE-FG2600-NT40932, describes the design and development of an engineered photobioreactor for CO_2 recycling at Ohio University, incorporating thermophilic organism research at Montana State University, and design work completed by the Oak Ridge National Laboratory to better utilize full-spectrum solar energy. The bioreactor design, which allows for suspension of viable thermophilic organisms on vertically-suspended growth surfaces, drastically reduces overall system footprint compared to the equivalent purely aquatic system. Further, by coupling full-spectrum, solar tracking photon collection and delivery via fiber optics allow the bioreactor to optimize growth and further reduce system footprint. Finally, coupling the delivery of water (during normal growth phase) and harvesting systems into the same fluid delivery mechanism has facilitated improved growth rates, while reducing system costs. Results of testing at our pilot-scale (5000 acfm) bioreactor have indicated that thermophilic cyanobacteria can grow in a sustainable, continuous fashion using only solar power in saturated flue gas. This paper will present our results to-date, as well as a brief analysis of system economics.

Introduction

It is generally believed that a portfolio of options will be needed to address the complexities of greenhouse gas emission control. Engineered photosynthetic systems offer advantages as a viable near-to-intermediate term solution for reduced carbon emissions in the industrial and energy sectors. Such systems could minimize capital and operating costs, complexity, and energy required to transport CO_2 that challenge sequestration for smaller fossil units. The potential for low cost control could be critical for smaller units, where capital cost per megawatt could be substantial for CO_2 control. For coal to remain competitive, especially in the rapidly emerging distributed generation market and to ensure future fuel diversification, low cost marginal control systems, such as photosynthetic systems, must be developed.

Despite the large body of research in the area of photosynthesis for carbon sequestration, little work has been done to create a practical system, one that could be used with both new and existing fossil generating units. For example, use of raceway cultivators ignores land availability limitations at many existing fossil generation plants. Few existing smaller generation units could find 1000+ acres of suitable land for siting and constructing a microbial pond. Additionally, how would the CO_2 be introduced to the photosynthetic agents? Would such a system need expensively separated CO_2 (not direct flue gas) for sparging, thus vastly increasing the system cost? Would local stack emissions restriction prevent dispersion of flue gas at ground level? In addition, questions exist about supply and distribution of light. For example, in a pond, only organisms near the surface would receive sufficient photons for photosynthesis due to the high degree of reflection and attenuation caused by the water. If organisms had to exist at the surface (and outside), would cold weather have a negative impact on their performance? Further, to keep any such system operating at maximum carbon uptake rate, mature and dead organisms would need to be harvested. How would that be accomplished and at what rate? Finally, although numerous post-harvesting uses exist, what would be the optimal use with respect to the specific application and host site? These questions – questions directly related to application of such a unit at any practical installation - must be addressed before deploying a practical photosynthetic system.

The concept behind engineered photosynthesis systems is straightforward. Even though CO_2 is a fairly stable molecule, it is the basis for the formation of complex sugars (food) by green plants through photosynthesis. The relatively high content of CO_2 in flue gas (approximately 14% compared to the 360 ppm in ambient air) has been shown to significantly increase growth rates of certain species of microalgae. Therefore, application is ideal for contained systems, engineered to use specially selected (but currently existing) strains of microalgae to maximize CO_2 conversion to biomass, absorbing greenhouse gases (Brock, 1978; Ohtaguchi et al., 1997). In this case, the microalgal biomass is the carbon sink.

For example, let's say the composition of "typical" microalgae (normalized with respect to carbon) is $CH_{1.8}N_{0.17}O_{0.56}$, then one mole of CO_2 is required for the growth of one mole of microalgae. Based on the relative molar weights, the carbon from 1 kg of CO_2 could produce increased microalgal mass of 25/44 kg, with 32/44 kg of O_2 released in the process, assuming O_2 is released in a one-to-one molar ratio with absorption of CO_2. Therefore, a photosynthetic system provides critical oxygen renewal along with the recycling of carbon into potentially beneficial biomass.

Enhanced natural sinks could provide an economically competitive and environmentally safe carbon management option because they do not require pure CO_2 and they do not incur the costs of separation, capture, and compression of CO_2 gas (Kajiwara et al., 1997; Hirata, et al., 1996). Among the options for enhanced natural sinks, the use of existing organisms in an optimal way in an engineered photosynthesis system is lower risk, lower cost, and benign to the environment. This contrasts the use of ocean-based sinks, which could present problems (Bacastow and Dewey, 1996). Large amounts of iron must be added to the ocean to promote additional CO_2 fixation. As a result, there may be little control over resulting growth. "Weed" plankton, the most likely organisms to grow, would not provide sufficient nutrients for the food webs, generating a high probability of negative environmental impact (Cooksey et al., 1995).

An engineered photosynthesis system could be placed at the source of the emissions to allow measurement and verification of the system effects, rather than being far removed from the emissions source, as is the case with forest-based and ocean-based natural sinks. The power source is natural and abundant. And the energy is converted to byproducts –biomass– that could be used as a fuel, fertilizer, feedstock, or source of hydrogen (Fisher, 1961). And even though some carbon is eventually released from biomass through decomposition, bioconversion is the fastest and safest method to add carbon to natural terrestrial sinks. Further, the process described in this paper also requires relatively small amounts of space, estimated to be 1/10th of a comparable raceway cultivator design. Because the organisms are grown on membrane substrates arranged much like plates in an electrostatic precipitator, there is little pressure drop. The system described here could be used at virtually any power plant with the incorporation of translating slug flow technology to create favorable conditions, such as reduced temperatures and enhanced soluble carbon concentration. Finally, engineered photosynthesis systems will likely benefit from current research into enhancing the process of photosynthesis, either genetically or via photocatalytic reactions.

Project Description

The conceptualized process, shown in Figure 1, begins after the flue gas has passed through suitable particulate control device(s) so that the gas will be substantially free of solid impurities. Then the flue gas must be cooled. In our concept, translating slug flow is used for both cooling the flue gas and generating soluble carbon species to “feed” the bioreactor. The water used in the process must also be cooled (using a cooling tower) due to solubility limitations of carbon dioxide in water. The cooled flue gas, and separately the soluble carbon from the slug flow reactor, pass through the bioreactor, which houses vertically suspended growth membranes growing thermophilic organisms, arranged to minimize pressure drop of the flue gas throughout the reactor. The growth substrate, which is a woven fibrous membrane, must be resistant to wear in the harsh environment of the flue gas and corrosive potential of the growth media and, because of the vertical position, offer a high degree of adhesion with the microalgae. However, the degree of adhesion can be too high, becoming problematic for harvesting.

Growth Media Transport System

The growth media transport system consists of two distinct parts – a circulating fluid system and liquid distribution system. The circulating fluid system is a closed looped, pump and gravity fed transmission system where water containing defined levels of nutrients and soluble carbon (or void of soluble carbon) is delivered to the membrane support for the organisms. The water then flows through distribution headers and then into the fibers by gravity assisted capillary action. A view of the capillary transport of water on a populated substrate is seen in Figure 2.

One of the more significant engineering challenges of this project is nutrient enhancement and delivery to the photobioreactor. Microalgae often more easily fix carbon and inorganic nitrogen in soluble form. Translating slug flow technology, developed at Ohio University's Institute for Corrosion and Multiphase Processes, not only increases concentrations of nutrients in the aqueous phase by directly removing them from the flue gas, but also lowers flue gas temperatures (Jepson, et al., 1993). Slugs create zones of greatly enhanced gas-liquid mass transfer, putting CO_2 and NO_x into soluble form for the microalgae. Such transfer would greatly speed up the natural process of photosynthesis, which in large-scale bioreactors, may be limited by the rate of diffusion of the carbon through the organism membranes.

Photon Collection and Delivery

Solar photons are the energy source of the system and one of the primary factors determining system efficiency. In order to utilize solar photons at maximum efficiency, the light delivery subsystem must deliver a sufficient quantity and quality of photosynthetic photons deep within the bioreactor and minimize the light loss due to reflection and adsorption. Direct, filtered sunlight is collected and delivered into the bioreactor, via collection optics and large-core optical fibers. As seen in Figure 1, the collector will mount outside the bioreactor, preferably on top of the reactor. The actual installed collector for the pilot-scale reactor is shown in Figure 3.

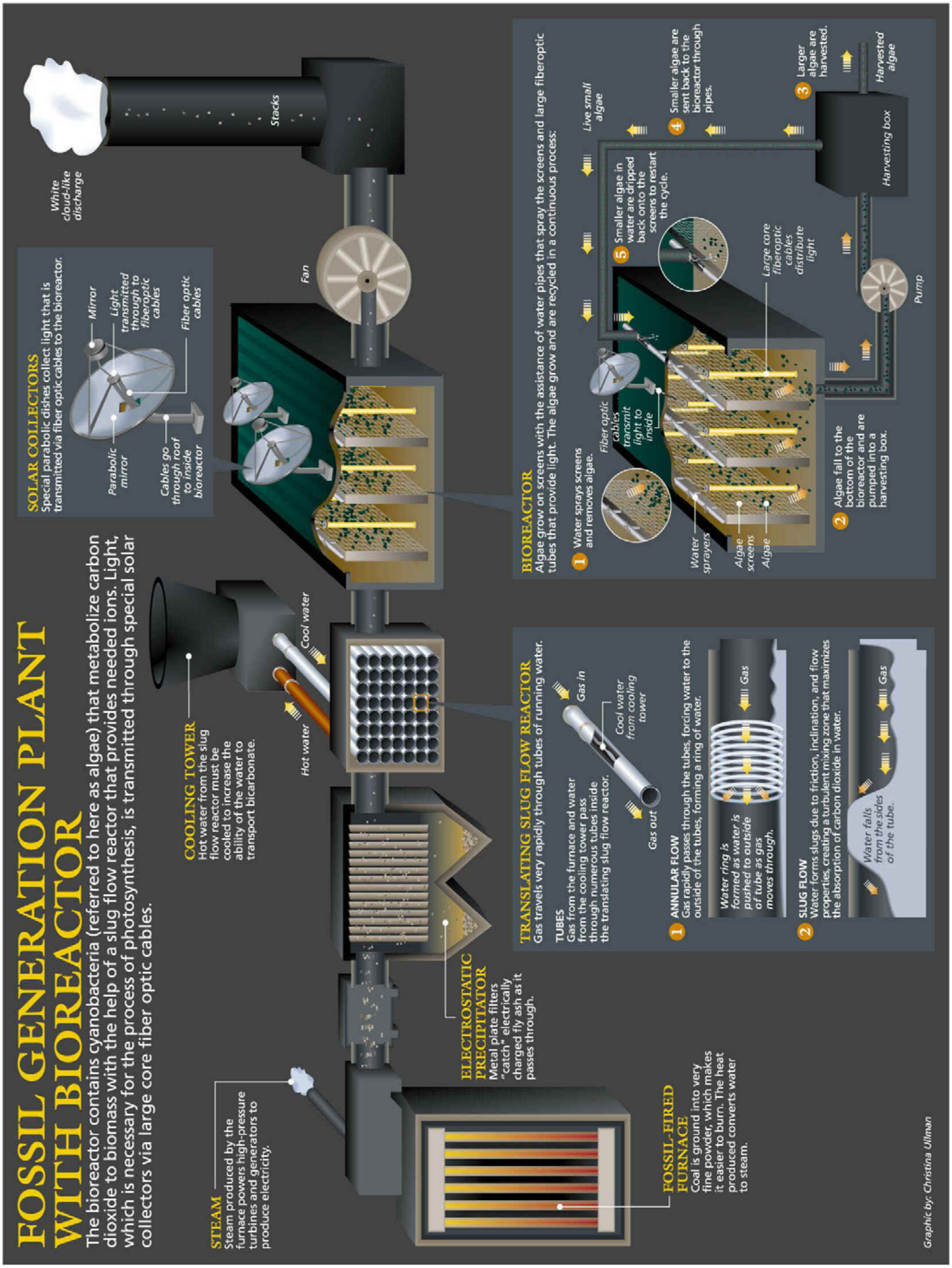

Figure 1. Artist’s concept of the bioremediation process

Figure 2. Populated substrates showing capillary transport of water

Figure 3. Solar Collector Mounted Above Pilot-Scale Bioreactor

The visible light from the sun reflected from collector dish and secondary optics is launched into an array of optical fibers. These large core fiber optic cables then supply photons necessary to support photosynthesis, using special distributors located between the vertical growth membranes (Figure 4).

By controlling attenuation through the fiber optic cables and using specially designed distributor plates made from similar materials, a uniform distribution of photons may be supplied, typically at a rate between 60-120 µmols m^{-2} s^{-1}. This distribution is a key element in reactor design. The sunlight, originally collected by tracking mirrors (optimizing solar collection) will provide over 2000 µmols m^{-2} s^{-1} of suitable photons throughout the day. However, at that rate, most photons would be wasted, as photosynthesis in thermophiles occurs at much lower levels of light.

Figure 4. Lighting panels with fiber optic leads

A further point of interest is that sunlight contains wide spectra of energy; some is useless to the photosynthetic organisms, such as infrared, and some is harmful, such as certain ultraviolet spectra. Filters remove unwanted portions of the solar spectra and allow it to be used for thermal photovoltaic production of electricity needed to power the auxiliary components of the system.

Organism Harvesting and Repopulation

The harvesting system provides a way to remove mature organisms, or reduce cell density to promote further cell division, as well as repopulate the membranes with developing organisms, thus maximizing carbon uptake. Preliminary tests indicate that microalgae, removed in "clumps" from the growth strata, are easily agitated into a diffuse state. Mature microalgae (organisms with a low potential for carbon utilization) can be removed and microalgae that are maturing, (organisms with a high potential for carbon utilization), can be repopulated on the growth strata.

The harvesting for the experimental bioreactor is done using the water distribution system to minimize needs for additional components. By increasing the water pressure to the distribution header, a great flow of water per unit area of membrane is achieved, creating a gentile washing effect. This gentle washing is critical, so as not to shock the organisms and delay continued growth. Further, the gentle washing process is generally 30-40% effective (on a mass basis) in removing organisms from the membrane substrate, which is needed to maintain cell density to sustain continued cell division. Illustrations of the membranes before and after washing are shown in Figures 5 and 6.

Figure 5. Membrane populated with microalgae

Figure 6. Membrane washed with the harvesting system

Potential Benefits

Several benefits, in addition to CO_2 mitigation, could result from this novel method of photosynthetic carbon conversion. Obviously, one advantage would be the generation of O_2 as a byproduct of photosynthesis. Another potential benefit would be electrical power generation. By using filters capable of separating the infrared region of the spectrum coupled to the solar photon collection and delivery system, the infrared portion of the spectrum could be directed to photovoltaics, which use the heat to generate direct-current electricity.

Another anticipated benefit would be reduction of additional gaseous pollutants including NH_3 (that slips through selective catalytic reduction for NOx control) and NOx (nitrogen oxides) that form from the combustion process. Work by Nagase et al. (2001) demonstrated considerable nitrogen assimilation from NOx species bubbled through a bioreactor and it is well established that NH_3 is an excellent source of nitrogen for many photosynthetic organisms.

Finally, the resulting biomass has numerous beneficial uses. In addition to being a potential fuel, microalgae have been used as soil stabilizers, fertilizers, in the generation of biofuels, such as biodiesel and ethanol, and to produce H_2 for fuel cells. In recent tests, it also has shown several positive ignition characteristics for cofiring with coal in pulverized coal-fired generation units.

Expected Cost of Deployment

For the purpose of this analysis, a power plant with a gross capacity of 200 MW, a capacity factor of 65% operating as a load-following unit (peaking during the day when solar photons are available), with a heat rate of 9000 BTU/kW-hr, burning a coal containing 70% carbon by mass and a higher heating value (HHV) of 12,000 BTU/lbm. The bioreactor for this economic case study is assumed to remove 50% of all CO_2 during daylight hours (during peak CO_2 production), and the incident photon flux on the solar collectors as delivered to the bioreactor is 1200 μmols m^{-2} s^{-1}. This value assumes that the only significant decrease in photon flux is not solar angle (overcome by mirror positioning), but cloud cover.

It should be noted that the key cost parameter is the cost of the solar collectors. It is estimated that the collectors, built by hand, would cost $30,000 a piece to install. Without mass production and economies of scale, $30,000 per collector would translate to $2,000 per ton of CO_2 removed from the flue gas. However, commercialization and mass manufacture of the solar collector technology is likely. The design team, headed by Oak Ridge National Laboratories, has received funding from DOE to further their hybrid lighting work. This technology is focused on use as a lighting system in commercial buildings. There current cost goal for their *building system* is $2,000/$m^2$ for light collecting.

In order to examine the effect of photon conversion efficiency at a collector cost of $2,000/$m^2$, Figure 7 was generated. Using the previously stated assumptions, the minimum cost for collection of one ton of CO_2 over the lifetime of the bioreactor, assuming continuous use, would be $80. Even assuming an extremely optimistic 30% conversion efficiency, the more likely cost is $240 per ton – ***with no revenue generated from the resulting biomass.***

However, current work by ORNL is to adjust the "building" system design to a "bioreactor" system design, employing solar collecting troughs and optic sheets instead of optic wires. The larger collection area and elimination for the need of several separate controllers drives the estimated cost of the unit to $400/$m^2$ of light collecting area. In that case (labeled as "proposed design"), the economics are very favorable ($48 per tons) if one assumes 30% conversion efficiency.

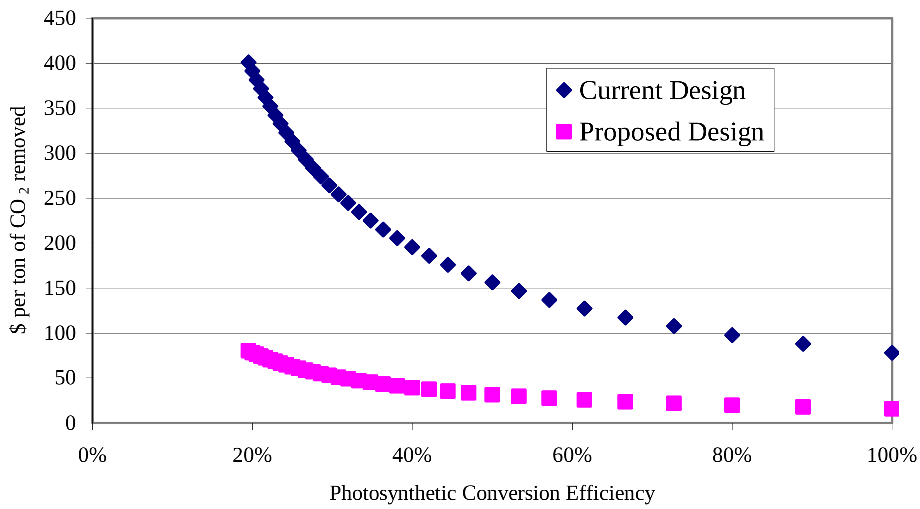

Figure 7. Cost of one ton of CO_2 removed as a function of photon conversion efficiency

If photon attenuation is reduced and deployment of such a unit occurs in a "sunnier" location, the incident photon level could increase to approximately 1500 μmols m^{-2} s^{-1}, the cost of CO_2 removal (per ton) for a conversion efficiency of 30% would become $39.

Conclusions

Because this is a work-in-progress, few significant conclusions can be drawn. However, the subsystem research has progressed to the point that a viable pilot-scale bioreactor is being constructed to test long term, sustainable and continuous conversion of CO_2 to biomass using collected solar photons. Further, this photobioreactor offers numerous possibilities for not only greenhouse gas mitigation, but also to control a wide variety of pollutants, notably NOx and ammonia slip, while producing a product that could have sustainable economic value.

Finally, it is clear that the economics of implementation are a significant hurdle to commercialization. Particularly, the cost of the solar collectors and photo distribution systems will be key to providing low-cost greenhouse gas emission remediation.

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